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Impact of walking on knee articular cartilage T2 values estimated with a dictionary-based approach - A pilot study

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ABSTRACT

Introduction: Walking is crucial for knee articular cartilage (KAC) health. Routine MRI sequences lack sensitivity for early cartilage changes, and the use of parametric T_2 maps to study the effect of walking on KAC composition is limited. This study aimed to evaluate if quantitative T2 maps using an Echo Modulation Curve (EMC) matching algorithm can detect KAC T2 variations due to water content changes after walking.

Methods: Seven asymptomatic volunteers (3 females, 4 males, mean age 28.3 years) without knee pathologies participated. Sagittal knee MRI scans were performed before and after a 9-min treadmill walk using a Modified Bruce protocol. T2-weighted Multi-Echo Spin-Echo KAC images were acquired at 3T. Tibiofemoral cartilage was segmented semi-automatically on three slices per knee, defining 39 KAC samples. Quantitative T2 maps were created using a dictionary-matching algorithm. Paired t-tests assessed exercise impact on KAC T2 values, independent t-tests compared group differences, and Friedman test with Bonferroni correction evaluated regional T2 changes.

Results: Walking increased KAC T2 values (mean difference (md) 0.61 ± 1.71 ms; $p = 0.016$). Significant differences were observed in "normal" BMI group (md 0.69 ± 1.27 ms; $p = 0.021$). Regional analysis revealed significant differences in medial femur in males (md 0.9 ± 2.1 ms; $p = 0.049$) and lateral tibia in females (md 1.4 ± 2.5 ms; $p = 0.046$). The medial tibia showed significant differences across sub-regions ($p = 0.026$).

Conclusion: Quantitative T_2 maps using the EMC matching algorithm detected consistent changes in KAC T_2 values after a short walking period.

Implications for practice: EMC quantitative T2 maps effectively detected knee cartilage changes post-walking. This technique could improve cartilage hydration assessments, aiding early detection in at-risk patients. It also suggests potential for personalized monitoring and rehabilitation, advancing musculoskeletal imaging and non-invasive joint health monitoring.

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Introduction

The knee articular cartilage (KAC) absorbs and redistributes daily biomechanical reducing friction in the articulation.[1] Excessive load can cause degeneration, but moderate activities like walking enhance KAC health by promoting blood flow and reducing inflammation.[2,3]

Magnetic Resonance (MR) imaging is the preferred modality for assessing cartilage pathology, as T_2 relaxation time reflects water content, collagen levels, and fibber orientation in the cartilage matrix.[4] Studies have shown that exercise influences the KAC T_2 values, which decrease after exercise.[5–10] Changes in cartilage hydration have also been observed after long-distance running and other activities like stair climbing and walking.[11,12]

Cartilage T_2 values are significantly affected by water content. Quantitative T_2 maps can detect small changes in hydration and collagen integrity associated with tissue deformation.[6] Typically, these maps are derived from a T_2 weighted multi-echo spin-echo (MESE) sequence, where the signal decay is recorded pixel-by-pixel and a mono-exponential decay curve is fitted to estimate the T_2 value[13] (Fig. 1-A) as given by the equation:

$$S(TE_i) = S_0 \cdot e^{(-TE_i/T2)}$$

where $S(TE_i)$ represents the signal intensity for the echo time TE_i and S_0 would be the signal at echo time $TE_i = 0$. This method can produce biased results due to stimulated and indirect echoes in the acquired signals.[14] Dictionary-based methods improve accuracy by matching the MESE data to a pre-computed dictionary of signal curves which account for all possible echo pathways - echo modulation curves (EMCs). The EMC maps are generated by solving the Bloch equations or applying the Extended Phase Graph formalism.[15] Using the precise radiofrequency (RF) pulse shapes and MESE protocol parameters (i.e. repetition time - TR, TE, flip angle - FA, and echo train length - ETL), a dictionary containing a list of theoretical EMC decay curves can be pre-computed, each corresponding to a specific combination of T_2 value and transmit B1+ field (Fig. 1-B). The best match between the measured MESE signal and the pre-computed EMC in the dictionary is identified to estimate the T_2 value in each pixel and has been shown to provide a more accurate T_2 estimate compared to simple mono-exponential fitting (Fig. 1-C).[16]

Recent studies using EMC maps to assess T_2 relaxation in the knee cartilage found that running may alter KAC structure, particularly in the weight-bearing medial compartment, while the lateral areas remain mostly unchanged.[17] Lindner et al.[18] observed lower T_2 values in the medial and lateral KAC compartments after partial meniscectomy, suggesting that running may excessively strain the KAC and that lower-impact aerobic exercise might be preferable. These studies highlight the potential of the dictionary matching method to deepen our understanding of exercise effects on KAC. However, no prior studies have investigated the impact of low-stress exercises, like walking, on cartilage composition using EMC-T2 maps.

This work sought to determine whether quantitative T2 maps created using the dictionary matching method applied to MESE data are sensitive enough to identify T2 variations in the KAC associated with water content changes after walking.

Methods

Volunteer recruitment

This pilot study, conducted from July 2021 to June 2022, is the initial phase of a larger prospective study investigating the use of quantitative EMC-T_2 maps in the KAC to assess physiological changes, before and after a half-marathon. Approved by the Institutional Ethics Committee (2018–203 (178-DEFI/177-CES)), all the volunteers provided written informed consent. Inclusion criteria were: ages ranging from 18 to 50 years; any ethnicity; filling out a Knee Injury and Osteoarthritis Outcome Score (KOOS) questionnaire with a score above 90. Exclusion criteria included incomplete informed consent; pregnancy; MRI contraindications; or knee, hip or spine pathologies identified by the KOOS questionnaire. All volunteers were screened for prior knee pathologies using the KOOS questionnaire[19,20] which evaluates knee symptoms and function across 5 subscales: Pain; other Symptoms; Function in Daily Living (ADL); Function in Sport and Recreation (Sport/Rec) and knee-related Quality of Life (QOL). Participants needed a score of 90–100 on each of the subscales for inclusion, which resulted in the recruitment of seven volunteers.[20]

Demographic data was collected at the time of the MR examination and included age, height, weight, body mass index (BMI) and knee dominance. Participants were categorized according to their BMI in the following categories[21]: “normal” (18.5 and 24.9 kg/m^2); “above” (25.0 and 29.9 kg/m^2); and “overweight” (above 30 kg/m^2). For data analysis, BMI categories were dichotomized into two categories: “normal,” and “above” (which also integrated the “overweight” subjects).

Exercise protocol

Participants were screened in the morning after a night's sleep and instructed to minimize physical activity before MRI acquisition. Each participant underwent an MR exam of both knees before exercise, followed by a 9-min treadmill walk at 2.7 km/h with a 5 % gradient inclination, without holding onto the handrail. This is a modification of Stage 2 of the Modified Bruce Protocol (MBP),[22] originally, a 3-min treadmill walk. The MBP was chosen due to its lighter impact on the physical condition, making it more suitable for individuals with moderate functional capacity.[23] The 9-min walk was chosen, based on the Ballady et al.‘s[24] recommendation of test protocols ranging from 6 to 12 min.

After exercise, participants returned to the MRI room, next to the exercise room, at a 12-s walking distance of about 10 m, to repeat the MRI scan of both knees. The total acquisition time (pre-exercise exam on both knees (20 min) + treadmill exercise (9m) + post-exercise exam on both knees (20 min)) was, approximately, 50 min.

MRI protocol

Scans were acquired using a 3-T MRI scanner (Achieva 3.0T TX; Philips Medical Systems, Best, The Netherlands) with a dedicated 8-channel knee coil. Participants laid supine on the MRI examination table with the non-scanned knee extended and the studied knee on the knee coil with a mean flexion of 10°. The non-dominant knee was always scanned first to minimize the influence of knee dominance on gait force distribution and KAC hydration.

Thirty sagittal T_2 slices of the KAC from both knees from each participant were acquired using an optimized T_2 MESE sequence,[25] with the following parameters: TR of 2057 ms; 10 evenly spaced echoes (TE's 5.9 ms–59 ms), with a step size of 5.9 ms; 2.5 mm slice thickness with no spacing; interleaved acquisition; 220 × 206 matrix; field of view 150 mm; 0.29 × 0.29 mm^2 in-plane pixel resolution; bandwidth of 48.5 kHz; 1 signal average and a total scan-time of 9:15 min.

An experienced MSK MRI researcher (ZC), with 12 years of experience, conducted all the acquisitions. The sagittal plane was consistently oriented using pre-specified standard anatomical

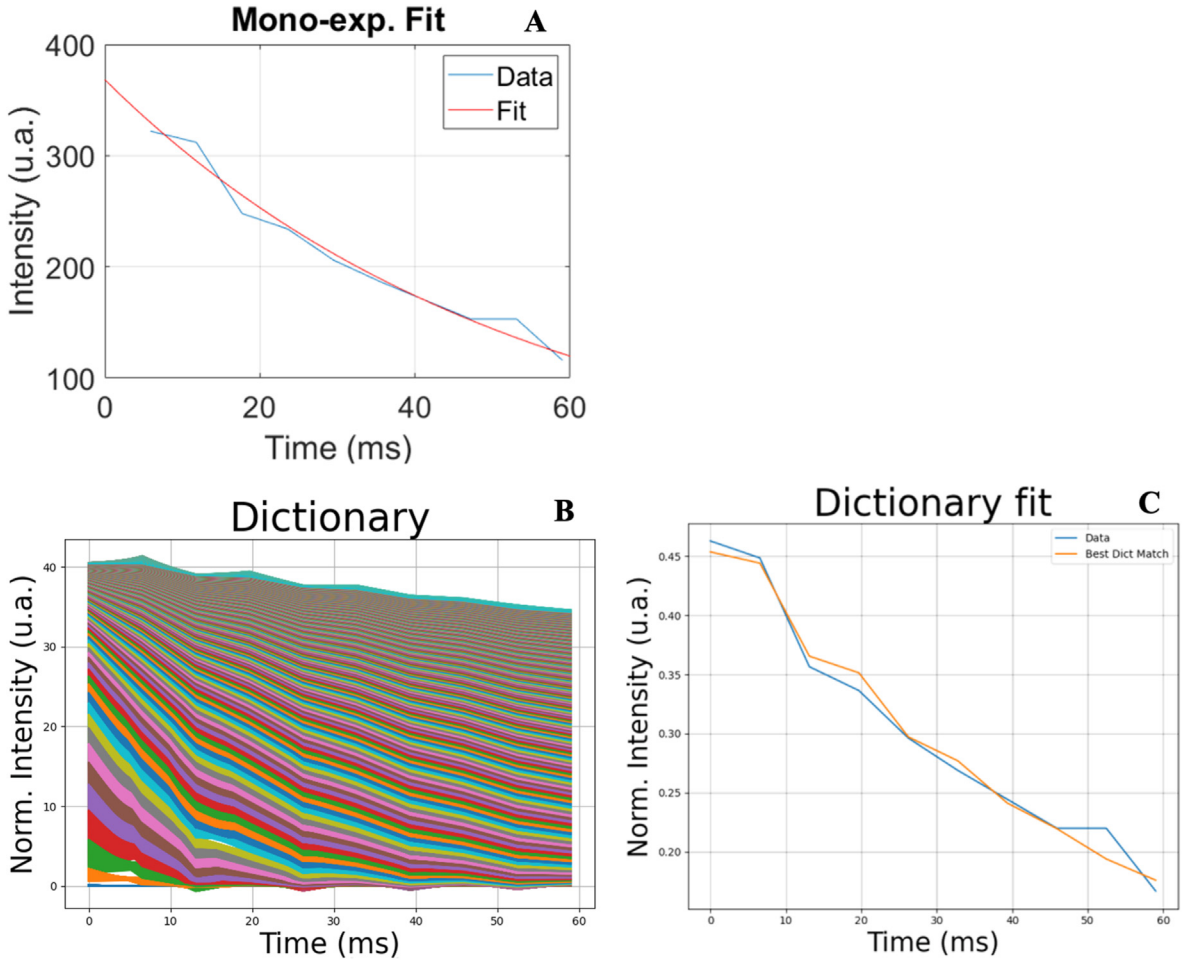

Figure 1. Quantitative T_2 decay approaches: Mono-exponential and EMC fitting to the T_2 Signal decay from one pixel. A) Mono-exponential fitting curve compared to the signal T_2 decay curve (Data). **B)** List of theoretical decay curves which will serve as a dictionary of simulated EMC curves for the T_2 decay. **C)** Dictionary fit to the pixel T_2 decay signal. (data from the investigator's database).

landmarks and was chosen to allow a better assessment of the KAC in a direction perpendicular to most of the weight forces. Ink markings applied on the skin surface over the anatomical bone landmark of the patella and tibial tuberosity during the first scan helped minimize positioning variations between scans. Each dataset, pre- and post-exercise, was categorized based on the knee side, dominance and exercise stage (e.g., 'dom_right_rest').

Image analysis

The same researcher (ZC) analysed and segmented pre- and post-exercise images using ITK-SNAP version 3.18.[26] The researcher was blinded to patient's identity and exercise condition to minimize potential bias and ensured objective analysis. KAC T_2-weighted sagittal images were screened for cartilage signal and morphology alterations and segmented in three consecutive central slices per condyle, using the coronal and sagittal views to select the most central and contiguous slices. These slices were ordered unequivocally from 1 to 3, from the outermost to the innermost (Fig. 2). A two-step semi-automatic approach was used for accurate cartilage segmentation: first, the semi-automatic tool segmented the deep cartilage from the underlying subchondral bone on the first echo image, then, manual correction on the last echo image refined the segmentation, allowing the separation of the superficial cartilage from the surrounding joint space and synovial liquid.

The femoral and tibial cartilages were divided into 4 major compartments according to the Whole-Organ Magnetic Resonance Imaging Score[27] (Fig. 3): medial femoral condyle (MF), lateral femoral condyle (LF), medial tibia plateau (MT) and lateral tibia plateau (LT). Each femoral condyle cartilage was additionally divided into 3 regions, defined by meniscus margins: anterior ("a") – from the anterior peripheral margin of the meniscus to the anterior-superior osteochondral junction; central ("c") – from the anterior margin of the anterior meniscus to the posterior margin of the posterior meniscus; and posterior ("p") – from the posterior peripheral margin of the meniscus to the posterior-superior osteochondral junction. The medial and lateral tibial cartilage were also divided into "a" (anterior), "c" (central), "p" (posterior) regions, with the anterior and posterior regions corresponding to areas covered by the meniscus and the central region being the weight-bearing zone between the meniscus horns.

Quantitative T_2 maps were generated with the T_2 KneeActive software tool available at (https://github.com/ZemaTimoteo/T2_KneeActive).[28] EMC matching involved creating dictionaries of EMC T_2 values ranging from 1 to 300 ms with a step size of 1 ms, T1 = 1000 ms and B1+ values ranging from 60 % to 140 % with a step size of 1 %, considering the sequence parameters and RF pulse excitation/refocusing flip angles (90°/125°), and their shapes. Despite the known difference between the selected T1 value and the expected KAC values, Ben-Eliezer et al. demonstrated that for

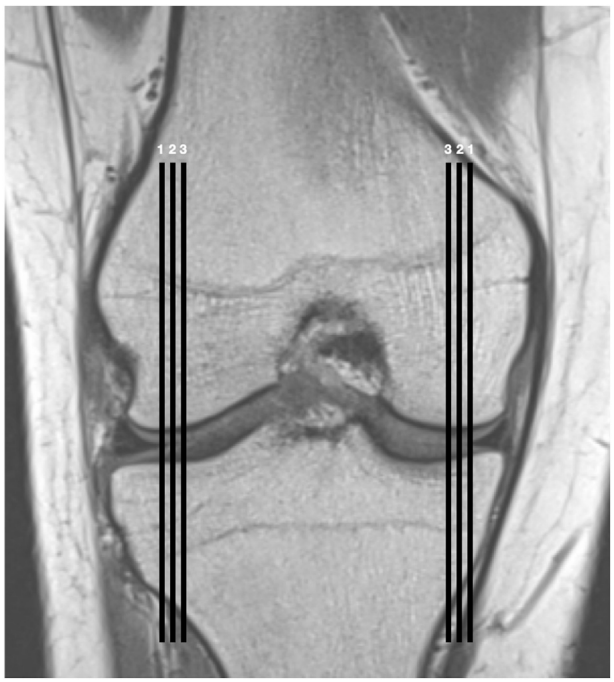

Figure 2. Example of slice ordering on 3 contiguous central slices selected for segmentation of the knee cartilage, from the outermost to the innermost slice.

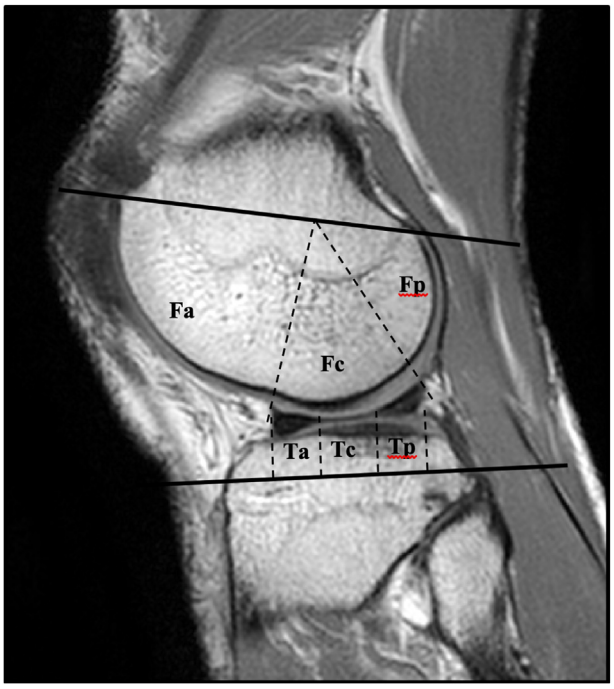

Figure 3. Whole-Organ Magnetic Resonance Imaging Score. The WORMS classification assesses 15 distinct regions, subdivided by anatomical landmarks, in the fully extended knee. The patella is divided into lateral facet (LP) and medial facet (MP), including the patellar ridge within MP. The femoral articular surface is divided into medial condyle (MF) and lateral condyle (LF), with the trochlear groove considered part of MF. Each condyle is further subdivided into three regions: anterior (a), central (c), and posterior (p). The medial tibial plateau (MT) and lateral tibial plateau (LT) are also divided into three regions: anterior (a), central (c), and posterior (p). Using the WORMS classification as a reference, the cartilage was divided in each sagittal image. **Fa** – femoral anterior; **Fc** – femoral central; **Fp** – femoral posterior; **Ta** – tibial anterior; **Tc** – tibial central; **Tp** – tibial posterior.

refocusing flip angles between 120 and 180°, and T1 values between 200 and 4000 ms, this parameter has a minimal impact on the EMC curves and, hence, the estimated T2 values.[29] Template matching was performed by identifying the EMC with the maximum dot product with each pixel echo series. The map was performed pixel-wise considering the segmentation mask of the KAC joint. Using the ITK-SNAP software, these EMC maps were superimposed on the last echo sagittal image to manually refine the region-of-interest (ROI) by removing pixels with a T_2 relaxation time greater than 150 ms, indicative of the presence of synovial liquid (Fig. 4).

Statistical analysis

Each slice was considered representative of one KAC sample and produced a total of 6 KAC regions per set (Femoral anterior, central and posterior; and Tibial anterior, central and posterior). For data analysis, each slice was ordered consecutively on a total of 13 knees, resulting in 39 valid samples.

The statistical analysis was performed using Microsoft Excel (version 16.72)[30] and IBM SPSS Statistics software (version 29.0).[31] For each KAC ROI, mean T_2 values (ms) and standard deviations were obtained. Statistical assumptions were based on the Shapiro-Wilk test, sample size, kurtosis and skewness.[32] Paired samples t-tests were used to analyse the exercise effect, while independent samples t-tests compared T2 values across dominance, BMI and gender. The Friedman test evaluated regional differences between cartilage condyles and sections, with Bonferroni correction for multiple pairwise comparisons. Pearson/Spearman tests assessed correlations between rest and stress T_2 values. P-values lower than 0.05 were considered statistically significant.

Results

Subject demographics

This study included 3 female and 4 male asymptomatic volunteers, with a mean age of 28.3 ± 8.0 years. Motion artefacts excluded one knee, leaving 13 valid knees for analysis, 6 right dominant and 1 left dominant. The mean BMI was 25.4 kg/m^2; with 20.5 kg/m^2 for the “normal” category and 30.9 kg/m^2 for the “above” category. None of the participants were involved in regular exercise or running programs.

Cartilage T_2 relaxation times: knee dominance, BMI and gender

The mean T_2 values for the entire KAC were 39.2 ms (±3.0 ms) at rest and 39.8 ms (±3.1 ms) post-stress (exercise), with a high correlation between pre- and post-exercise values ($r = 0.845$; $p < 0.01$). The differences in mean KAC T_2 values before and after stress were statistically significant (0.61 ± 1.71 ms; $p = 0.016$). Knee dominance had a subtle effect on cartilage T_2 ($p = 0.04$), with a minor increase in the total T_2 post-walking values on the dominant knees. No significant differences in T2 values at rest or post-stress were observed across BMI categories (Table 1) but significant differences were noted within the “normal” BMI group, with a T2 increase after stress ($p = 0.021$).

Mean T_2 values before and after stress showed statistically significant differences between male and female groups ($p < 0.001$) (Table 1), with females exhibiting higher T_2 values at rest compared to males, and this inter-group T_2 relationship remained in the stress condition.

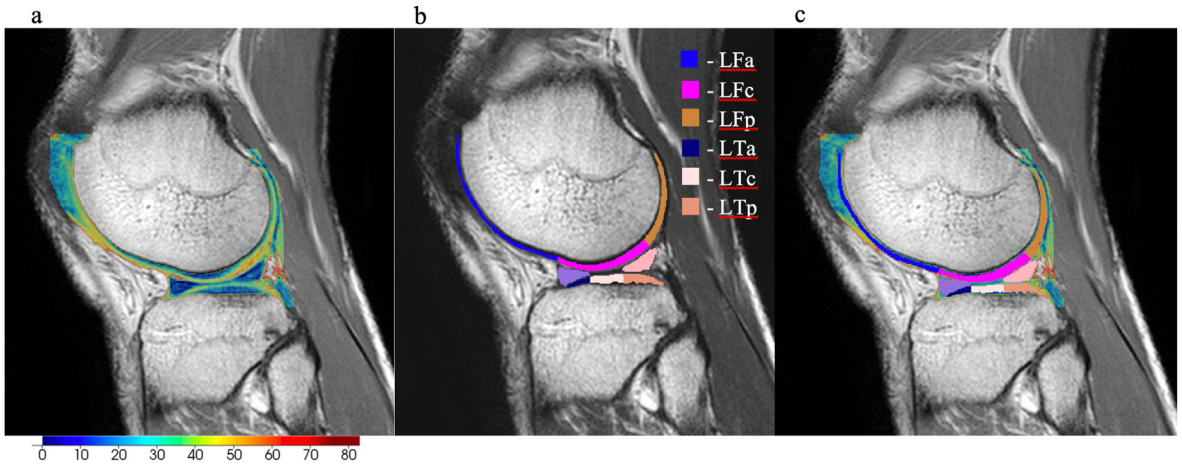

Figure 4. T_2 Quantitative T_2 mapping. (a) EMC-T_2 map superimposed onto the respective sagittal T_2 slice with T_2 colour bar in ms. **(b, c)** Example of the segmented cartilage components superimposed onto the sagittal slice (b) and EMC-T_2 map (c).

T_2 of the lateral and medial knee compartments

Table 2 displays the effect of walking on KAC T_2 values across the femoral condyles and tibial plateau. KAC segments showed a general slight increase in bulk T2 of all compartments with significant differences between stress and rest T_2 values in the non-dominant knee in LF (0.8 ± 1.6 ms; $p = 0.037$). Comparing BMI categories, at rest, the 'normal' group exhibited higher T_2 cartilage values in all compartments compared to the 'above' group, without significant differences in T_2 values. Although KAC T_2 values at rest appeared to be influenced by BMI (LF compartment, $p < 0.05$), this effect normalized after exercise. Significant differences between stress and rest were observed in the MF ($p = 0.043$) for the "normal" group and in MF for males ($p = 0.049$), whereas females showed significant differences in LT ($p = 0.046$).

T_2 of the femoral and tibial cartilage regions

The individual cartilage sections exhibit a T_2 pattern similar to the condyles with slight variations in mean and SD values (Table 3). Given the orientation of the sagittal slices and the specific slice selection for studying the weight-bearing cartilage, certain marginal slices failed to cover all KAC regions, particularly the anterior LF and MF regions. After stress, T_2 values in the central section of MT increased by 2.6 ms ($p = 0.024$) (Table 3). The only compartment where differences between rest and stress were different among regions was the MT (test statistics 7.316, $p = 0.026$). Post-hoc pairwise comparisons with Bonferroni correction showed significant differences in T_2 values between the anterior and the central sections of the MT (test statistics −2.604, $p = 0.009$), anterior versus posterior (test statistics −1.812, $p = 0.070$) and central versus posterior (test statistics 0.793, $p = 0.428$). The remaining KAC regions were not statistically significant, as shown in Table 3.

Discussion

This study investigated the impact of a 9-min inclined treadmill walk on KAC hydration using MRI quantitative T_2 relaxation maps. Recent studies using EMC-generated T2 maps to assess high-impact exercises on cartilage hydration[17,18] reported similar rest T_2 KAC values for healthy and post-meniscectomy knees.

Table 1
Cartilage mean T_2 values by knee dominance, BMI categories and gender before and after stress.

		n	T_2 Rest (ms)	T_2 Stress (ms)	Difference (ms)	Paired t-test statistics	p-value
			Mean ± SD	Mean ± SD	Mean ± SD		
Total T_2		39	39.2 ± 3.0	39.8 ± 3.1	0.61 ± 1.71	2.532	0.016[a]
Dominance	Dom	21	39.6 ± 3.0	40.2 ± 3.1	0.60 ± 1.26	2.192	0.040[a]
	nDom	18	38.7 ± 2.9	39.5 ± 3.2	0.79 ± 2.14	1.567	0.135
	Independent t-test statistics		0.965	0.723			
	p-value		0.341	0.474			
BMI	Normal	21	39.4 ± 2.6	40.1 ± 3.1	0.69 ± 1.27	2.495	0.021[a]
	Above	18	38.9 ± 3.4	39.6 ± 3.3	0.69 ± 2.15	1.371	0.188
	Independent t-test statistics		0.504	0.472			
	p-value		0.617	0.640			
Gender	Male	24	37.7 ± 2.2	38.6 ± 2.8	0.82 ± 2.05	1.953	0.063
	Female	15	41.4 ± 2.6	41.9 ± 2.5	0.49 ± 0.94	2.006	0.065
	Independent t-test statistics		−4.728	−3.788			
	p-value		<0.001[b]	<0.001[b]			

n – number of samples (KAC slices); **nDom** – non dominant; **Dom** –dominant.
[a] Significant 0.05.
[b] Significant 0.01.

Table 2
Effect of stress on the T_2 values for femoral and tibial cartilage of the lateral and medial compartments by knee dominance, BMI and gender.

				LF					LT					MF					MT				
		n		Rest (ms)	Stress (ms)	Difference (ms)	% Mean diff.	Paired t-test statistics p-value	Rest (ms)	Stress (ms)	Difference (ms)	% Mean diff.	Paired t-test statistics p-value	Rest (ms)	Stress (ms)	Difference (ms)	% Mean diff.	Paired t-test statistics p-value	Rest (ms)	Stress (ms)	Difference (ms)	% Mean diff.	Paired t-test statistics p-value
All samples		39	Mean ±	41.6 ±	41.9 ±	0.3 ±	0.7%	0.930	37.9 ±	38.7 ±	0.8 ±	2.1%	1.280	39.8 ±	40.5 ±	0.7 ±	1.8%	2.26	37.3 ±	38.3 ±	1.0 ±	2.7%	1.539
			SD	3.0	2.8	2.0		0.358	7.1	7.6	4.0		0.208	2.6	2.3	1.8		0.029*	3.8	5.19	4.0		0.132
Dominance	nDom	18	Mean ±	41.0 ±	41.8 ±	0.8 ±	2.0%	2.266	36.4 ±	37.6 ±	1.3 ±	3.6%	1.130	39.6 ±	40.6 ±	1.0 ±	2.5%	2.074	37.7 ±	37.7 ±	0.0 ±	0.0%	0.056
			SD	2.7	3.3	1.6		0.037*	7.2	7.3	4.70		0.274	2.1	2	2.1		0.054	4.7	5	3.1		0.956
	Dom	21	Mean ±	42.1 ±	41.9 ±	-0.2	-0.5%	-0.373	39.2	39.7	0.4 ±	1.0%	0.609	40.0	40.4	0.4 ±	1.0%	1.040	37.0	38.8	1.8 ±	4.9%	1.811
			SD	3.3	2.4	2.2		0.713	6.9	7.9	3.3		0.549	3	2.5	1.6		0.311	3	5.4	4.6		0.085
			Independent test statistics p-value	-1.121	-0.073	1.649			-1.259	-0.827	0.636			-0.532	0.314	1.155			0.574	-0.628	-1.382		
				0.270	0.942	0.108			0.216	0.413	0.529			0.598	0.755	0.255			0.570	0.534	0.175		
BMI	Normal	21	Mean ±	42.7 ±	42.9 ±	0.2 ±	0.5%	0.532	38.3 ±	38.9 ±	0.6 ±	1.6%	0.902	39.1 ±	39.9 ±	0.8 ±	2.0%	2.162	37.4 ±	38.6 ±	1.2 ±	3.2%	1.095
			SD	2.3	2.8	1.8		0.6	7.2	7.6	3.0		0.378	2.1	2.4	1.7		0.043*	4.2	6.3	4.9		0.286
	Above	18	Mean ±	40.4 ±	40.7 ±	0.4 ±	1.0%	0.755	37.4 ±	38.5 ±	1.1 ±	2.9%	0.920	40.6 ±	41.1 ±	0.52 ±	1.3%	1.073	37.2 ±	38.0 ±	0.80 ±	2.2%	1.167
			SD	3.4	2.4	2.2		0.461	7.2	7.9	4.9		0.370	2.8	2.1	2.0		0.298	3.4	3.7	2.9		0.259
			Independent test statistics p-value	2.510	2.520	-0.284			0.368	0.149	-0.373			-1.835	-1.699	0.464			0.226	0.386	0.282		
				0.017*	0.016*	0.775			0.715	0.882	0.711			0.076	0.098	0.646			0.823	0.701	0.780		
Gender	Male	24	Mean ±	40.5 ±	41.3 ±	0.8 ±	2.0%	2.057	34.3 ±	34.7 ±	0.4 ±	1.2%	0.457	39.4 ±	40.3 ±	0.9 ±	2.3%	2.081	36.7 ±	37.9 ±	1.2 ±	3.3%	1.223
			SD	2.1	2.1	1.9		0.051	4.6	5.5	4.7		0.652	1.7	1.7	2.1		0.049*	4.2	5.8	4.7		0.234
	Female	15	Mean ±	43.4 ±	42.9 ±	-0.5 ±	-1.2%	-0.971	43.7 ±	45.1 ±	1.4 ±	3.2%	2.195	40.4 ±	40.7 ±	0.3 ±	0.7%	0.906	38.2 ±	38.9 ±	0.7 ±	1.8%	1.004
			SD	3.5	3.4	2.0		0.348	6.6	6.1	2.50		0.046*	3.5	3	1.4		0.380	3.2	4.2	2.7		0.332
			Independent test statistics p-value	-2.885	-1.804	2.037			-5.217	-5.482	-0.747			-1.005	-0.514	0.893			-1.181	-0.578	0.364		
				0.003**	0.079	0.049*			<0.001**	<0.001**	0.460			0.328	0.613	0.377			0.245	0.567	0.718		

n – number of samples (KAC slices); **nDom** – non dominant; **Dom** –dominant; **LF** – Lateral Femur; **LT** – Lateral Tibia; **MF** – Medial Femur; **MT** – Medial Tibia;

* significant 0.05; ** significant 0.01

Table 3
T_2 mean values by cartilage region in each knee compartment before and after stress.

Section			n	Mean ± SD (ms)	Number of complete pairs	Mean difference ± SD (ms)	% Mean difference	Paired t test statistics	p-value	Friedman statistics	p-value
LF	Anterior	Rest	39	41.4 ± 4.0	34	−0.3 ± 4.1	−0.7 %	−0.447	0.658	0.418	0.811
		Stress	39	41.1 ± 4.1							
	Central	Rest	39	40.6 ± 3.8	39	0.5 ± 2.5	1.2 %	1.329	0.192		
		Stress	39	41.1 ± 3.9							
	Posterior	Rest	39	42.4 ± 5.2	39	0.8 ± 3.6	1.7 %	1.338	0.189		
		Stress	39	43.1 ± 4.4							
LT	Anterior	Rest	39	37.2 ± 7.2	39	0.8 ± 3.9	2.2 %	1.224	0.229	1.213	0.545
		Stress	39	38.0 ± 8.4							
	Central	Rest	39	35.3 ± 8.4	39	0.6 ± 4.7	1.7 %	0.770	0.446		
		Stress	39	35.9 ± 8.5							
	Posterior	Rest	39	41.2 ± 8.2	39	1.1 ± 5.2	2.7 %	1.313	0.197		
		Stress	39	42.3 ± 8.4							
MF	Anterior	Rest	39	38.2 ± 4.6	32	1.0 ± 3.8	3.1 %	1.533	0.136	5.871	0.053
		Stress	39	39.4 ± 4.1							
	Central	Rest	39	35.7 ± 3.2	39	0.6 ± 2.3	1.7 %	1.608	0.116		
		Stress	39	36.3 ± 2.9							
	Posterior	Rest	39	45.1 ± 4.6	39	0.1 ± 1.9	0.4 %	0.435	0.66		
		Stress	39	45.3 ± 4.5							
MT	Anterior	Rest	39	38.7 ± 3.6	39	−0.4 ± 3.4	−1.0 %	−0.767	0.448	7.316	0.026[a]
		Stress	39	38.3 ± 4.0							
	Central	Rest	39	34.3 ± 5.6	39	2.6 ± 6.8	7.6 %	2.360	0.024[a]		
		Stress	39	36.9 ± 9.6							
	Posterior	Rest	39	38.6 ± 6.1	39	1.1 ± 5.5	2.8 %	1.231	0.226		
		Stress	39	39.7 ± 6.7							

n – number of samples (KAC slices); **LF** – Lateral Femur; **LT** – Lateral Tibia; **MF** – Medial Femur; **MT** – Medial Tibia.
[a] Significant 0.05.

The increase in T_2 values post-walking suggests that even short periods of continuous walking can influence KAC hydration. While previous research has shown decreased KAC T_2 values after high-impact exercises like running,[33,34] few studies have addressed walking's effect on T_2. One study reported a 3 % reduction in KAC T2 after 30 min, with values normalizing after 25 min.[12] Our study found a 1.8 % T2 increase in the MF, likely due to initial cartilage dehydration followed by recovery and water retention phase. Another study observed a similar hydration response, with T2 increases in the LT (3.0 %) and LF (1.5 %) KAC after 10 min of cycling, which did not recover after 20 min[35] These findings suggest that low-impact walking does not lead to persistent KAC dehydration in young individuals, aligning with evidence that regular walking promotes joint health by increasing KAC synovial fluid.

Minor T_2 variations related to BMI, gender and knee dominance were observed, with limited effects on cartilage hydration post-stress. Normalization of post-stress T2 values suggests that scanning the non-dominant knee first may have mitigated dominance-related hydration effects. However, despite instructions to minimize physical activity before MRI scans, uncontrolled variables like diet and gait mechanics could have influenced the results. Future research should implement stricter controls and assessments of these variables to better isolate the effects of walking on cartilage hydration.

Mild walking reduced BMI-related hydration differences, aligning with research showing that light exercise benefits knee health regardless of BMI.[17,33,34] Gender-specific T2 responses were also observed, reflecting anatomical and biochemical differences influenced by sex hormones.[36–38]

Our study found that walking affected the medial tibiofemoral cartilage and lateral femoral cartilage regions, especially their central sections, with significant T_2 increases. This aligns with data suggesting increased medial compressive forces during walking, affecting the anterior and central MF and anterior MT cartilage.[39,40] Cross-referencing with Meng Chen et al.'s[12] findings, the areas most dehydrated after a long walk (LT, MF and LF) were approximately the same that showed higher hydration levels in our study, suggesting that moderate walking may help rehydrate knee cartilage in areas prone to dehydration after a more intense exercise.

KAC health is essential for quality of life, and MRI parametric mapping is essential to detect early changes, although limited by long acquisition times. Faster MRI techniques such as MRI Fingerprinting could overcome this by providing rapid and simultaneous estimation of multiple tissue-related parameters.[41,42]

Our quantitative EMC-T_2 maps were previously validated in both phantom and *in vivo*.[43] The EMC model can be extended to account also for the impact of other physical parameters such as B0 inhomogeneities or diffusion and, recently, quantitative T_2 maps constructed with EMC matching algorithms have been applied to different regions, including the brain,[44] muscle,[45,46] and articular cartilage of the hip[47] and knee.[18,44] To our knowledge, no prior studies analysed the impact of walking on the T_2 cartilage using EMC-T_2 maps.

Despite the encouraging results, the sample size was small, and the specific imaging protocol might have limitations, with a TE value for the first echo (5.9 ms) limited by image quality and hardware performance. More sensitive techniques enabling shorter echo time acquisition, such as Ultrashort Echo Time (UTE) could provide further clarity.[48,49] Additionally, T_2 mapping is susceptible to the "magic angle" artefact associated with the anisotropy of collagen architecture, which influences T2 values and, consequently, the appearance of KAC on MRI images.[4] In our study, the anterior LF/MF sections exhibited prominent effects, but this should not have affected our conclusions, as similar effects were observed in the post-stress samples.

The primary objective of this work was to explore the feasibility of using EMC-T_2 maps to detect changes in KAC hydration after walking. This study is a novel application of a dictionary-based method to T_2 mapping which, despite its recent development, seems to offer more reliable T_2 values across different clinical settings and equipment, outperforming the conventional mono-exponential approach. Given the exploratory nature of this study, a

small sample size was considered sufficient to identify preliminary trends and justify larger-scale studies. Future research will try to include a larger and more diverse cohort, including elderly population, to validate these findings and improve their robustness and statistical power.

Although this study focused on the short-term effects of walking, the results suggest that EMC-T_2 maps could be a valuable tool for long-term monitoring of cartilage health. Over time, this method could improve screening protocols and support personalized interventions aimed at maintaining joint health. Potential long-term clinical applications include the early detection of cartilage degeneration, personalized rehabilitation programs, and improved management of joint health in at-risk populations, highlighting the potential of EMC-T2 maps in musculoskeletal care.

Conclusion

Quantitative T_2 maps generated with EMC algorithms revealed increased T_2 values post-walking, suggesting potential cartilage hydration. This study highlighted the influence of anatomy, biomechanics, and individual differences on cartilage response. Further research will be warranted to optimise exercise parameters for joint health and expand the application of EMC-T_2 maps in detecting physiological changes.

Authorship contribution statement

JMC: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision, Project administration. **TTF:** Software, Validation, Formal analysis, Resources, Data Curation, Writing - Review & Editing. **SMA:** Validation, Formal analysis, Writing – review & editing. **RGN:** Validation, Writing – review & editing, Supervision, Funding acquisition. **LN** Validation, Conceptualization, Writing – review & editing, Supervision, Project administration. **AO:** Validation, Writing – review & editing, Supervision, Project administration.

Conflict of interest statement

None.

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